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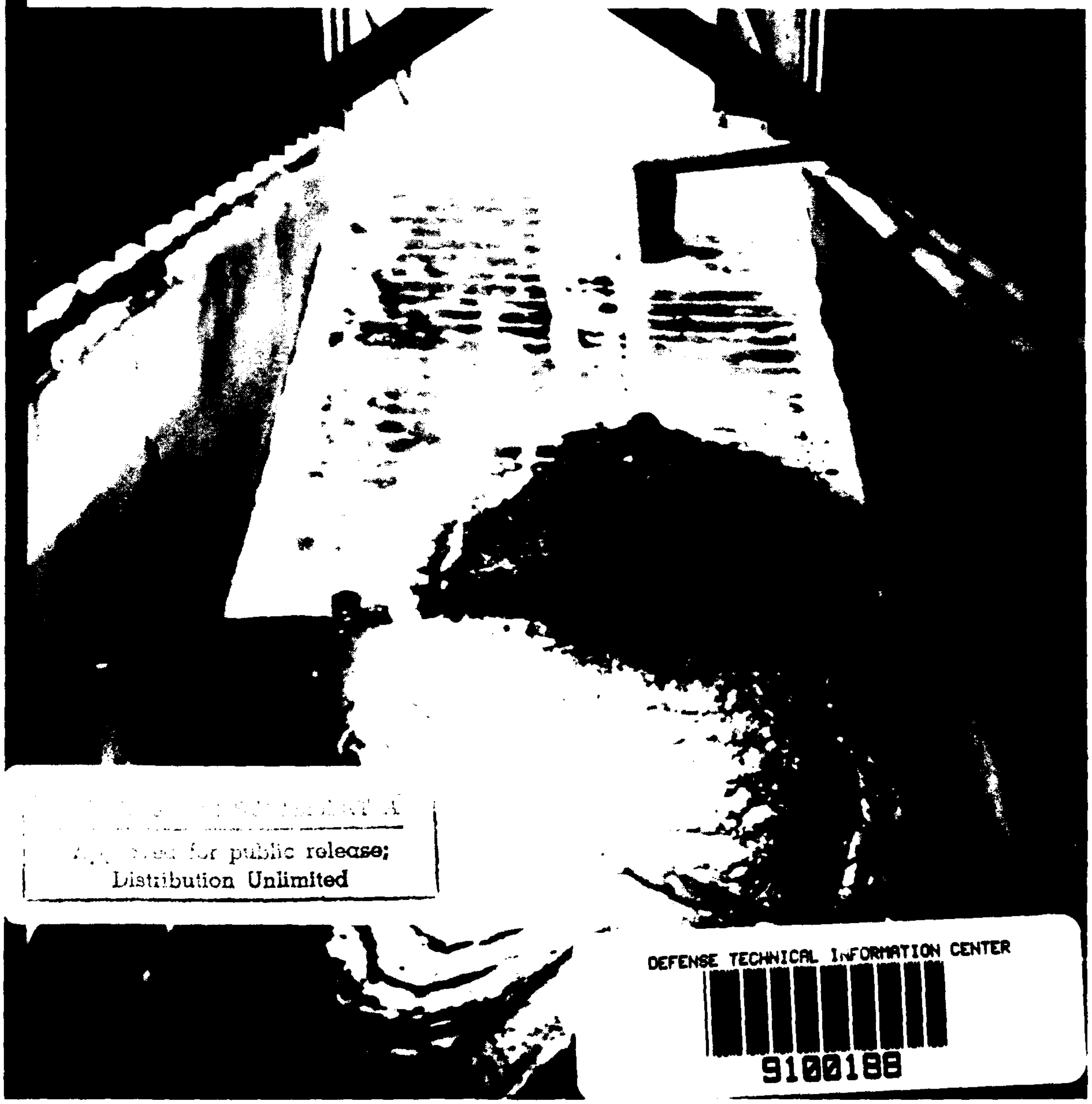
Sludge Dewatering in a Freezing Bed

A Pilot-Scale Study

C. James Martel and Carl J. Diener

April 1991



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Freezing bed during application of anaerobically digested sludge.

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U.S. Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

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PREFACE

This report was prepared by Dr. C. James Martel, Environmental Engineer, and Carl J. Diener, Civil Engineering Technician, Civil and Geotechnical Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by DA Project 4A762784AT42, *Cold Regions Engineering Technology*, Task BS, *Installation Management and Operation;* Work Unit 051, *Freeze–Thaw Separation of Sludges, Including Those With Hazardous Materials.*

The authors thank Don Elder of the Hanover Sewage Treatment Plant in Hanover, New Hampshire, and Barry Brownell of the Woodstock Sewage Treatment Plant in Woodstock, Vermont, for supplying the sludge used in this research.

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Sludge Dewatering in a Freezing Bed
A Pilot-Scale Study

C. JAMES MARTEL AND CARL J. DIENER

INTRODUCTION

The ability of natural freeze–thaw to dewater sludges has been known for several decades. One of the first recorded accounts was that of Babbitt (1931), who noted that sludge drained and dried very quickly if it was left to freeze in the drying beds over the winter. This dewatering effect is thought to occur during the formation of ice crystals, which grow by incorporating pure water molecules into their structures. During crystal growth, impurities such as sludge solids are rejected to the ice crystal boundaries, where they are compressed and dehydrated. When this frozen material is thawed, the ice crystals melt and the solids remain in a compressed state. Dewatering is achieved when the meltwater is drained away. Earlier column studies (Martel 1989a) indicated that up to 2.0 m of stabilized wastewater sludge can be dewatered by this method.

Some northern treatment plants have successfully used natural freeze–thaw in their lagoons or drying beds. Although effective, these techniques are often labor intensive and do not fully utilize the winter freezing season. A typical example is the Lakewood Water Treatment Plant in Duluth, Minnesota, where sludge is frozen by pumping it from the bottom of the lagoon to the overlying frozen surface.

To maximize the amount of sludge dewatered by natural freeze–thaw, a specially designed unit is necessary. The USA Cold Regions Research and Engineering Laboratory (CRREL) has developed such a unit operation, called a sludge freezing bed. Basically the bed consists of an in-ground concrete basin with a drainage system for removing meltwater during thaw. Since snow accumulations would insulate the sludge and thus reduce the rate of freezing, the bed is covered with a roof. In extremely cold climates, this roof could be made from a transparent material to allow passage of solar radiation, which should increase the thawing rate in the spring. Blowing snow is kept out of the bed by surrounding it with a louvered sidewall. A conceptual sketch of this bed is shown in Figure 1.

The freezing bed would be operated as follows. During the winter the operator would apply sludge to the bed in 8- to 10-cm layers. Ideally each layer would be applied soon after the previous layer had frozen. This procedure would maximize the total depth of sludge frozen in the bed. At the end of the freezing season, the bed would contain approximately 1 m of frozen sludge, depending on local climatic conditions. These frozen sludge layers would then be allowed to thaw during spring and summer. As the sludge thawed, the meltwater would be drained away by lowering the stop planks at the overflow gate and opening the drain valves. When

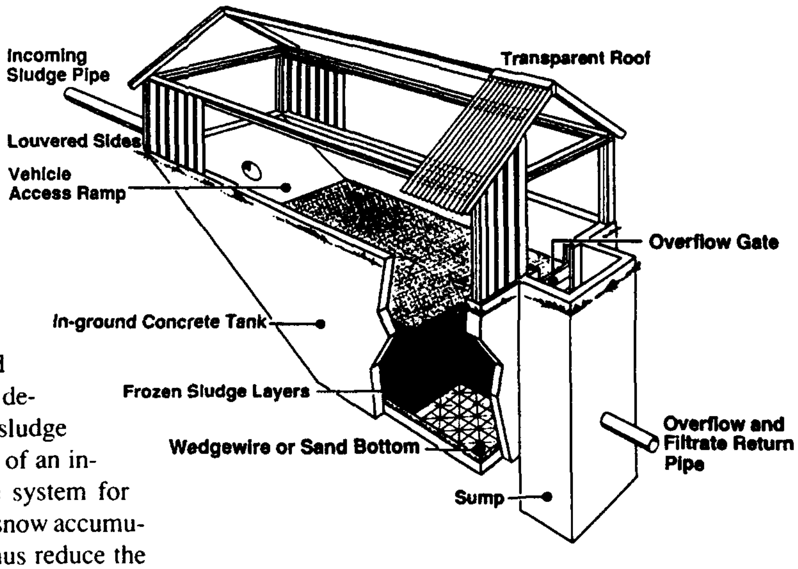


Figure 1. Sludge freezing bed.

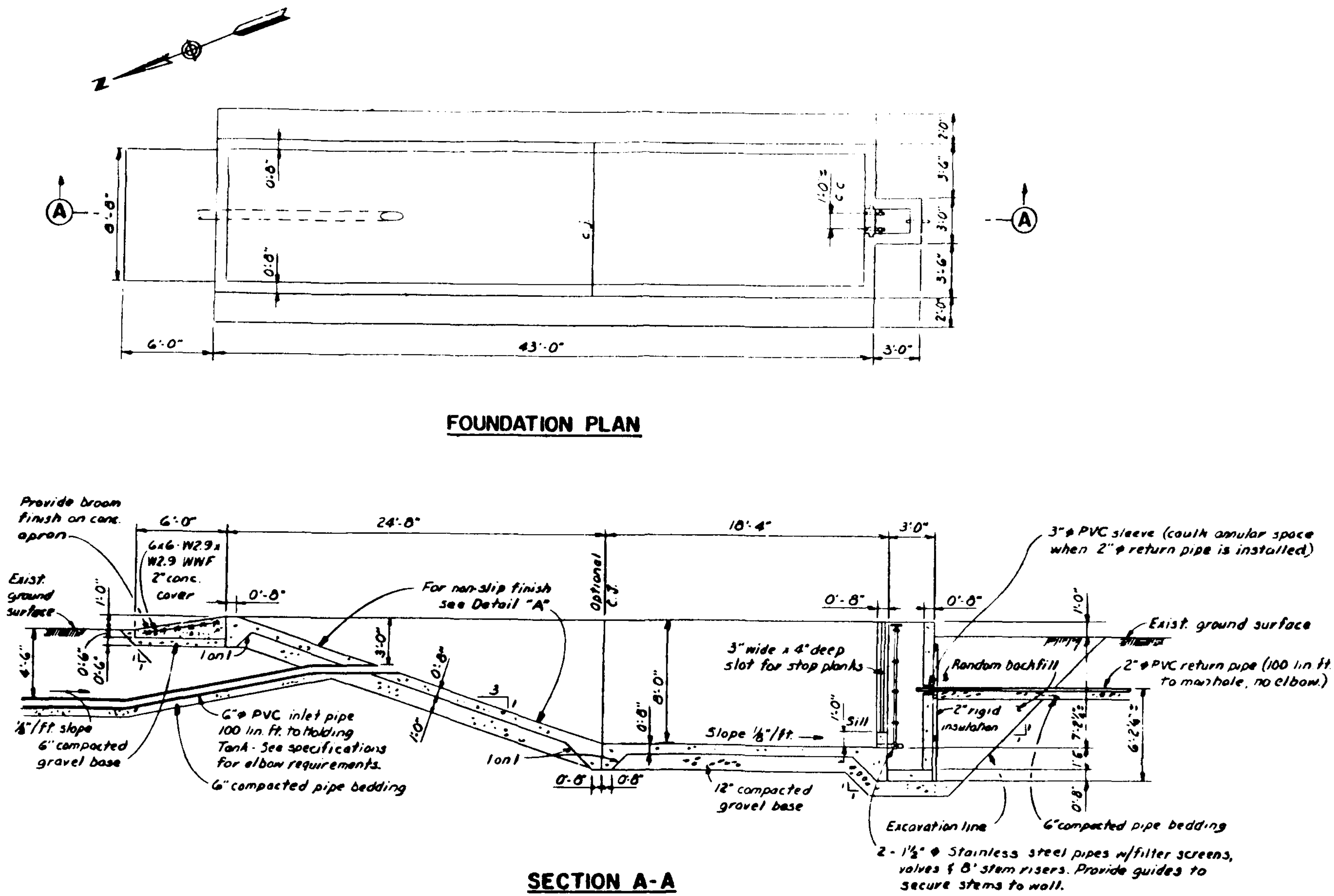


Figure 2. Construction drawing of the pilot-scale sludge freezing bed.

Figure 3. Pilot-scale sludge freezing bed.

all the sludge had thawed and drained, the operator would remove the remaining sludge solids with a front-end loader.

To test this concept, a pilot-scale freezing bed was constructed at CRREL in Hanover, New Hampshire. Construction began in the fall of 1986 and was completed by January 1987. The overall dimensions of the bed are 13.1 m long by 2.4 m wide by 2.4 m deep (Fig. 2). The ramp, walls and floor of the bed are made of concrete with type Y and type U waterstops at the joints. The concrete walls are insulated on the outside with 5 cm of Styrofoam. The roof consists of a wood frame covered with transparent panels of corrugated Fiberglas. Instead of louvered sidewalls, the bed is surrounded with 1.2-m-high exterior-grade plywood panels. The remaining space above these panels was left open to allow free air movement through the bed. A pair of swinging gate-type doors at the ramp end and a small door at the sump end were installed to allow access to the bed (Fig. 3).

The main purpose of this study was to evaluate the CRREL freezing bed concept for dewatering typical wastewater treatment sludges. To accomplish this evaluation, the pilot plant was operated over the winters of 1986–87, 1987–88 and 1988–89 (for purposes of this report, year 1, year 2 and year 3, respectively). Anaerobically digested sludge was applied to the bed during year 1 and year 2. Aerobically digested sludge was applied during year 3. The performance was measured in terms of the depth of sludge frozen, the time required for freezing and thawing, the meltwater quality and the total solids content in the sludge before and after treatment.

Another purpose of this study was to validate proposed design models for freezing beds. Details on the development of these models can be found in Martel (1988a,b,c, 1989b). Temperature and insolation data for the models were obtained from monthly data booklets provided by the Hanover Meteorological Detachment of the U.S. Army Atmospheric Sciences Laboratory. Cumulative degree-hours during freezing and thawing were calculated from these data by accumulating the product of average daily temperature and 24 hours.

OPERATION AND PERFORMANCE

Year 1

The anaerobically digested sludge was obtained from the Hanover Sewage Treatment Plant. This sludge contained an average total solids content of 6.7%. It was stored in a 7500-L concrete holding tank buried in an embankment 10 m from the ramp end of the freezing bed. This tank was connected to the freezing bed with a 15-cm-diameter plastic pipe buried approximately 90 cm below grade.

Each layer was applied manually by activating a motorized ball valve that allowed sludge to flow into the bed by gravity. It took approximately one minute to apply each 8-cm layer. The extent of freezing was determined by chipping or drilling a hole in frozen sludge each day. When no liquid was observed in the hole, the layer was judged to be frozen and another layer of liquid sludge was applied. The temperature of the applied sludge ranged from 0° to 6°C.

Because of construction delays, the first layer of sludge was not applied until 20 January 1987. Five more layers ranging in thickness from 2.5 to 14 cm were frozen during the rest of the freezing season. The dates of application of each layer, along with the depth of sludge in the bed, are shown in Figure 4. By 11 March, 58 cm of sludge had been frozen. Even more sludge could have been frozen had it not been for a frozen pipeline, which prevented sludge applications during the 12-day period from 28 January to 9 February. Several factors caused this problem. First, the discharge pipe appeared to lack sufficient pitch to facilitate com-

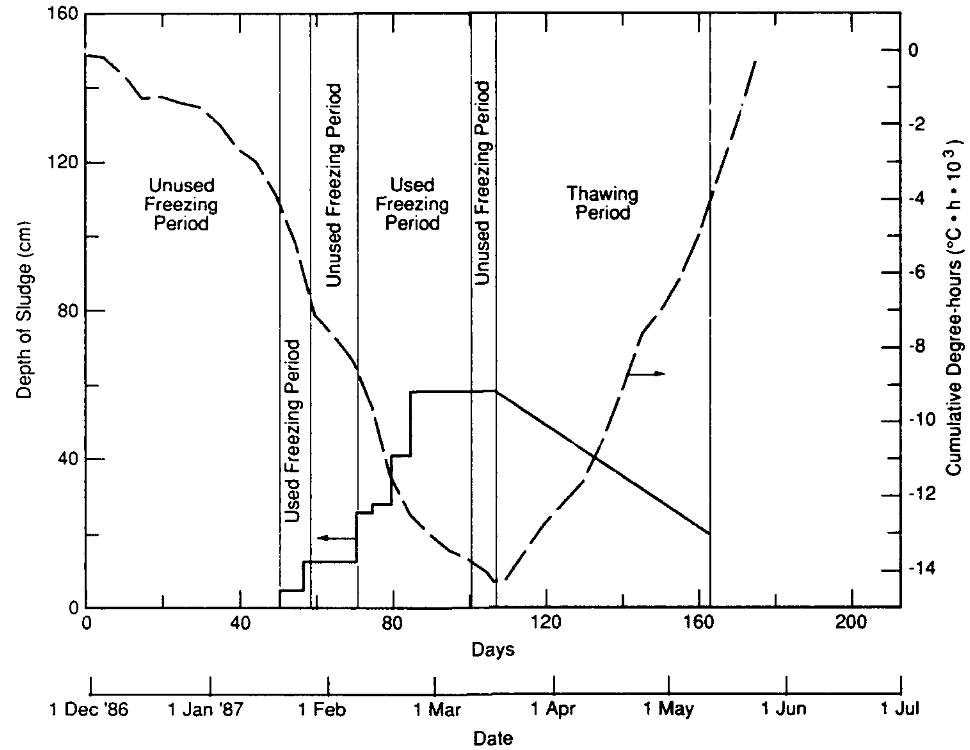


Figure 4. Depth of sludge and cumulative degree-hours in year 1.

plete drainage after each layer was applied. Since much of the pipe was above the frost line, this may have allowed remnants of each discharge to freeze to the pipe walls. The result was restricted flow and finally complete blockage. We were able to thaw the line by manually flushing it with hot water.

According to the cumulative degree-hour plot shown in Figure 4, the freezing period began on 1 December 1986 and ended on 20 March 1987. Of the –14,220 °C-hr accumulated during this period, only –7,600 °C-hr were actually used to freeze sludge because of the late start and the frozen pipline. The thawing period began on 20 March and ended on 11 May 1987, when all the frozen sludge was finally thawed.

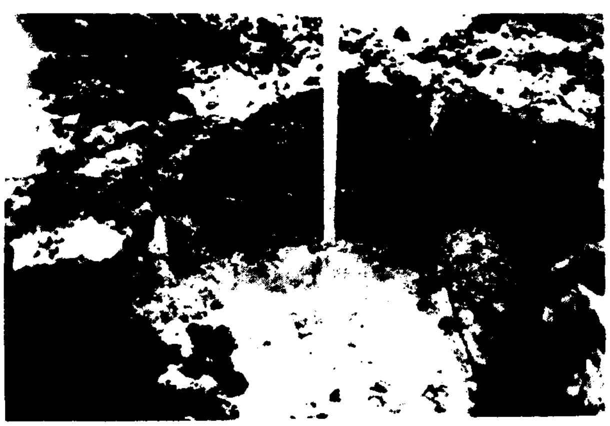


Figure 5. Dewatered anaerobically digested sludge during year 1.

The first indication of thawing was a gradually widening gap between the frozen sludge and the sidewalls of the bed. Thawing then progressed from the sides inward and from the top downward. Meltwater seemed to drain away as quickly as it formed, and cracks began to appear on the surface of the sludge. As expected the sunny portions of the bed thawed faster than the shady portions. By 11 May all sludge was thawed, leaving 25 cm of dewatered sludge on the underlying sand (Fig. 5). The average dry solids content of this dewatered sludge was 39.3%, which represents an 83% reduction in water content. Shortly thereafter the sludge was removed with a front-end loader and used in a local garden as a soil conditioner. Odor was not a problem during the entire thawing and removal process.

Year 2

Because of the problems experienced during year 1, we decided to modify the freezing bed and its sludge application system. These modifications are significant enough to require explanation before the second year's operation and performance are discussed.

The most significant change was relocation of the storage tank from its buried hillside location to a gravel pad adjacent to the bed. With the storage tank in this

Figure 6. Storage tank in new location next to freezing bed.

Figure 7. Back wall of freezing bed, showing wall and floor drains.

location, the feed pipe could be shortened and placed above ground for easy removal in case of freezing. Since the tank was now in an exposed above-grade position, it was insulated with 10 cm of Styrofoam insulation and covered with plywood paneling. A sealed submersible motor with a shaft-mounted propeller was placed in the tank to keep the sludge well mixed. Also, the control valves and associated electrical equipment were enclosed in a small insulated and heated utility shed next to the storage tank. Figure 6 shows the storage tank in its new location.

Inspections of the bed after the first year of operation indicated that the water stops at the floor and wall joints were improperly installed. As a result, we were afraid that leaks could develop in the bed. To solve this problem we covered the floor of the bed with 10 cm of additional concrete. Also, the stop planks were replaced with drain valves staggered stepwise every 7.5 cm. The stop planks were replaced because they leaked and were difficult to remove during thaw. Figure 7 shows these modifications.

Based on previous observations of how easily meltwater drained away from sludge after freeze–thaw (Martel 1989a), we decided to forego the sand layer at the bottom of the bed. If this modification was possible, it would eliminate the need for sand and thus reduce the operating costs. However, the sludge did not drain and other means had to be found to remove the filtrate.

As mentioned earlier, the operational plan for the bed calls for each layer to be applied as soon as the previous layer had frozen. This moment sometimes occurred during off-duty hours when nobody was available to apply the next layer. For example, if a layer became frozen overnight or over a weekend, the next layer would not be applied until the operator returned to work. Therefore, some freezing time was wasted. To solve this problem, we built an automatic sludge applicator that discharges a layer whenever a preset number of freezing degree-hours have elapsed. The required number of freezing degree-hours needed to freeze a layer of known thickness can be predicted from a mathematical model (Martel 1988a) or determined from experience. Details on the development of this device can be found in Appendix A.

On 11 November 1987 the sludge holding tank was filled with tap water and the automatic sludge application system was tested. The test was a success, taking one minute to apply an 8-cm-thick layer of water. The freezing bed was then filled to a depth of 45 cm and observed for evidence of leaks. No leaks were found, so the bed was drained and prepared for receiving sludge. The first load of sludge was trucked in from the Hanover Sewage Treatment Plant and loaded into the sludge holding tank. The average solids content in this anaerobically digested sludge was 5.4% for all the loads received during year 2.

The first layer of sludge was applied on 1 December. Because of abnormally warm weather, this layer did not freeze until 30 December. However, the onset of colder weather in January and the continuation of this weather through February allowed 14 more layers to be frozen, for a total depth of 1.14 m. As shown in Figure 8, all of the freezing period was used to freeze these layers. A total of −12,300°C·h was recorded during this period.

Most of the layers were applied manually because the automatic sludge application system did not prove to be reliable enough for unsupervised operation. The system malfunctioned on several occasions and had to be reset. Consequently we did not feel comfortable re-

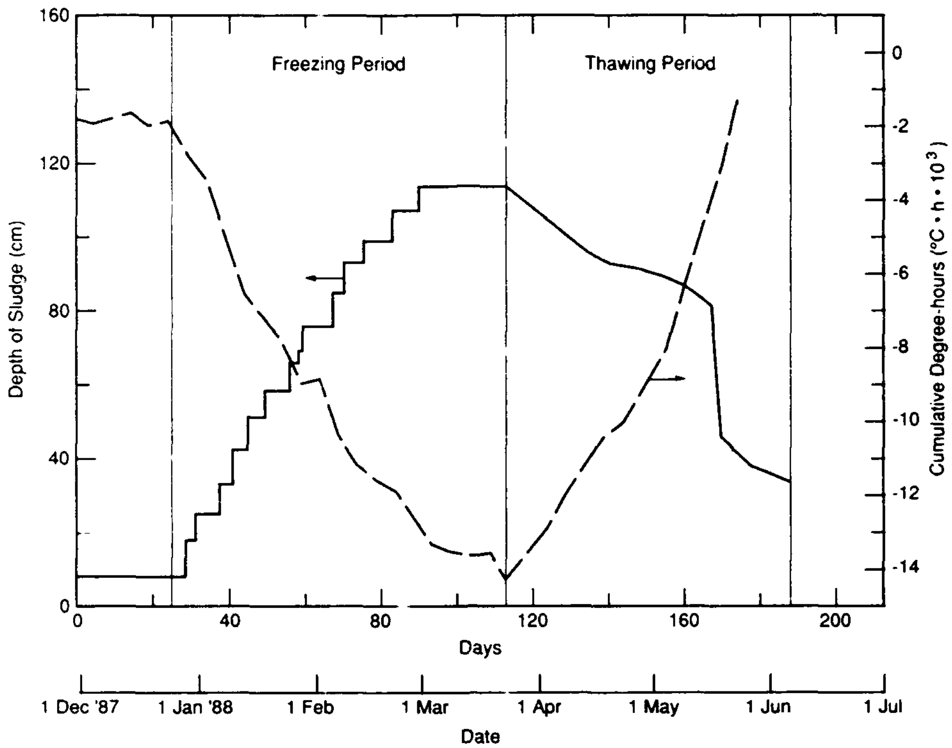


Figure 8. Depth of sludge and cumulative degree-hours in year 2.

lying on it to apply sludge during off-duty hours. Instead we inspected the bed daily including weekends and applied each layer manually as before. If the automatic system had been operating, perhaps we could have frozen even more sludge.

Observations during several freezing events revealed that each layer began to freeze along the sidewalls of the bed. We think this occurs because the concrete walls are already below the freezing point and act as a heat sink. Freezing then progressed inward from the sidewalls and downward from the exposed surface of the sludge layer. The last place to freeze was near the center of the bed. Freezing of sludge in this manner (i.e. in thin layers) did not appear to cause any structural damage to the bed. However, the partially frozen layer occasionally ruptured because of expansion during freezing.

The last layer applied to the bed (layer 15) did not freeze completely in an area along the west wall. The reason it did not freeze was the increasing intensity of incoming solar radiation at the end of the freezing period. The sun was now high enough to strike this part of the bed for several hours each day. To freeze this layer, we had to shade the sunny portion with sheets of plywood. This problem suggests that freezing beds should be covered with an opaque rather than a transparent roof. Also, the sidewalls around the bed should be high enough to shade the bed. Preventing solar radiation from striking the bed should be acceptable practice in a temperate climate like Hanover, New Hampshire, where solar radiation is not needed to thaw the sludge before the next application season. However, in colder climates where thawing depth is the limiting design criterion, the heat input from solar radiation will be needed to thaw the sludge prior to the next freezing season.

According to the cumulative degree-hour plot (Fig. 8), the thawing season began on 23 March. Instead of allowing the meltwater to quickly drain out as in year 1, we kept the drain valves closed and allowed it to accumulate. This change was an attempt to increase the thawing rate of the frozen sludge layers. Theoretically a thawed sludge layer that is wet would have a higher thermal conductivity than one that is dry. This idea proved to be impractical because the wet thawed sludge layer became anaerobic and began to produce odors. Therefore, on 13 May we decided to remove the meltwater by opening the bottom drain valves. To our disappointment, the flow rate through these valves quickly slowed to a trickle and eventually ceased altogether. The reason for this stoppage appeared to be the reduced surface area available for drainage caused by our earlier decision not to provide a sand layer over the bottom of the bed. It appears that a sand layer at the bottom of the bed is critical for adequate drainage during thaw.

By 6 June, thawing was complete, but because of the lack of drainage the sludge was not able to dewater.

Therefore, we decided to let the sludge remain in the bed until the water evaporated and the sludge was dry enough for removal. After several weeks, the sludge was removed with a front-end loader and returned to the Hanover plant for disposal. No solids analysis was conducted on the final product.

A grab sample of the meltwater contained a biochemical oxygen demand (BOD) of 301 mg/L, total suspended solids (TSS) of 110 mg/L, turbidity of 85 NTU and pH of 7.6. These concentrations are equivalent to those found in a raw wastewater. Therefore, the return of this meltwater to the head of the plant should not upset downstream wastewater treatment processes.

Year 3

No structural modifications were done to the bed for year 3. However, a layer of sand was placed in the bottom of the bed as in year 1. Also, we applied aerobically digested sludge to the bed instead of anaerobically digested sludge. The aerobically digested sludge was obtained from the Woodstock Sewage Treatment Plant in Woodstock, Vermont, and it contained an average solids content of 1.1%. As shown in Figure 9, a total of 89 cm of sludge was frozen between 1 December and 17 February. According to the cumulative degree-hour plot, it took –10,600°C·h to freeze this depth of sludge. Even more sludge could have been frozen because not all of the freezing period was used.

On 17 January, we stopped applying sludge to investigate a "leak" that had developed after an extra thick layer of sludge was applied sometime over the weekend between 13 and 16 January. This layer was 13 cm thick, and it was applied on top of a partially frozen layer of sludge. We suspect that this release was caused by a malfunction in the automatic sludge applicator. Soon after this extra thick layer was applied, we observed a slow drop in the liquid level, indicating that sludge was somehow escaping from the bed. Most of the liquid appeared to escape along the sidewalls, especially in the southeast corner and the western sidewall near the ramp. We tried to stop these "leaks" by packing them with snow. This worked to some extent, as we were able to freeze several more thin layers. However, some leakage continued, so we stopped applying sludge and excavated the frozen sludge in the vicinity of the leaks. We expected to find a crack in the bed caused by the expansion of ice during freezing. This was not the case. Instead we found several vertical channels down the side of the bed between the concrete wall and the frozen sludge. These channels were connected to a series of small caverns underneath the previously frozen sludge. Apparently, these caverns served as storage sites for liquid sludge leaking down from above. At the time of the investigation, these caverns were empty, which was surprising since all drains were closed.

What appears to have happened is that the heat

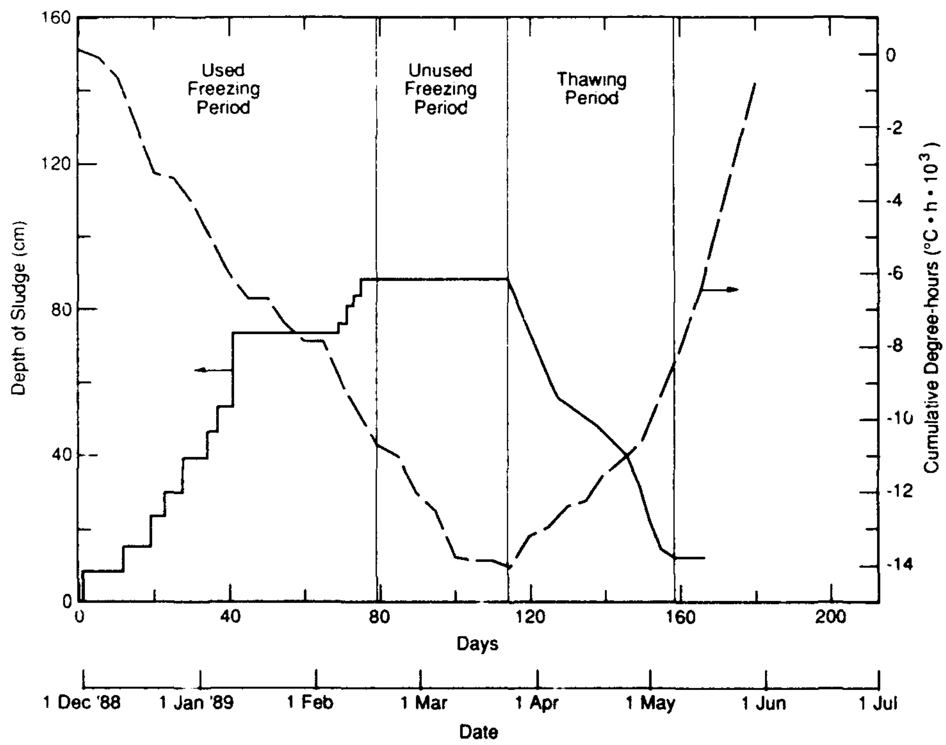
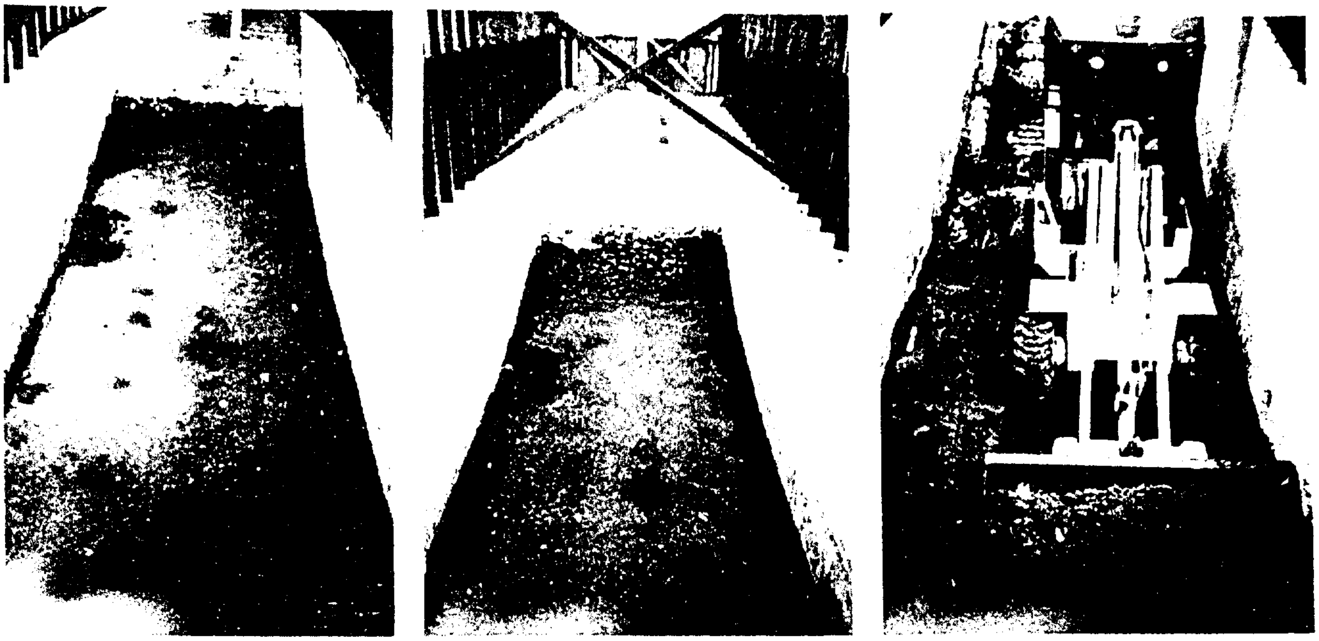


Figure 9. Depth of sludge and cumulative degree-hours in year 3.



a. 19 April 1989. b. 5 May 1989. c. 19 June 1989.

Figure 10. Condition of sludge in freezing bed during thawing period in year 3.

contained in the extra thick layer was enough to melt the frozen bond between the concrete walls and the previously frozen sludge. This allowed liquid sludge from the surface to flow into the underlying sand layer. The sand layer was probably unsaturated, and the addition of water caused it to consolidate. As a result, the sand layer separated from the overlying frozen sludge, forming the caverns. Over several days, most of this water may have escaped through small cracks in the concrete, causing the caverns to empty. These caverns were then refilled when the next layer was applied, giving the appearance of leaks.

The development of "leaks" in the bed and the resulting deposition of unfrozen sludge on the sand layer did not seem to restrict drainage during thaw. However, this could become a serious operational problem if large areas of the sand layer were affected. To avoid this potential problem, leaks should be plugged as soon as possible. As mentioned earlier, one technique that proved reasonably successful was to pack the leak with snow.

According to the cumulative degree-day plot in Figure 9, the thawing period began on 24 March. Unlike year 2, there were no problems with the drainage system, which confirms the importance of the sand layer. The filtrate drain valves were opened as soon as the sludge began to thaw, allowing the meltwater to drain out of the bed and into the sump. No meltwater was allowed to collect as supernatant and thus no odors were produced. Portions of the bed that received the most sun thawed noticeably faster. By 7 May, all the sludge in the sunny areas of the bed was thawed, whereas several centimeters remained frozen in the rest of the bed. By 19 May, all the sludge had thawed, leaving 13 cm of dewatered solids. Samples of the sludge taken on 23 May contained 24.5% solids, which means that the freezing bed removed over 95% of the water from the original sludge. The sludge, along with the sand layer, was removed with a front-end loader on 20 June. Figure 10 shows the operation of the sludge freezing bed during year 3.

The meltwater from the bed was quite strong, as indicated by the data in Table 1. These concentrations are equivalent to those of a medium to strong sewage (Metcalf and Eddy 1979). As indicated earlier, the return of this meltwater back to the head of the plant should not be a problem.

Table 1. Meltwater quality from freezing bed during year 3.

Date	*BOD (mg/L)*	*COD (mg/L)*	*TSS (mg/L)*	*Turbidity (NTU)*	*pH*
4/12/89	432	1100	112	125	7.1
4/18/89	268	800	111	80	6.9
4/26/89	391	900	121	175	7.1
5/03/89	241	600	69	100	6.5
5/23/89	—	300	66	100	7.0
Average	333	740	96	116	6.9

VALIDATION OF DESIGN MODELS

The size of a freezing bed will depend on the depth of sludge that can be frozen and thawed under the natural climatic conditions at the proposed site. In this section, mathematical models for predicting these depths are presented and evaluated against the results obtained from this pilot plant study. Also, approximate geographical limits to these models are identified.

Freezing model

Martel (1988c, 1989b) proposed the following model for predicting the freezing design depth D_f:

$$D_f = \frac{P_f\left(T_f - \bar{T}_{af}\right)}{\rho_f L\left(\frac{1}{\bar{h}_c} + \frac{\varepsilon}{2K_{fs}}\right)} \quad (1)$$

where P_f = freezing period
T_f = freezing point temperature
$\bar{T}_{af}$ = average ambient temperature during freezing
ρ_f = density of the frozen sludge
L = latent heat of fusion
$\bar{h}_c$ = convection coefficient
ε = thickness of the frozen sludge layer
K_{fs} = conductivity coefficient of the frozen sludge.

Table 2 lists suggested values for these variables. This model assumes that the bed will be operated as follows:

- Sludge is applied in layers and each layer is applied as soon as the previous layer has frozen. This means that the freezing progress of each layer must be monitored. As discussed earlier, this can be accomplished manually by periodically poking holes in the freezing sludge layer, or automatically with a degree-hour counting device.
- The temperature of the sludge applied to the bed is at the freezing point. If the sludge is warmer than 0°C, some of the underlying sludge may melt and would require refreezing. However, for practical purposes, a sludge temperature a few degrees above the freezing point should not cause a significant error. One case where this would not be true is when sludge is applied from a heated digestor.
- The entire freezing season is used for freezing sludge. This includes weekends and holidays.
- The surface of the bed is kept free of snow. No time is allowed for snow removal operations. This will not be a problem if the bed is covered as recommended.

Table 2. Suggested values for each parameter in eq 1 and 2 (Martel 1989b).

Variable	*Value*	*Source*
ρ_f	917 kg/m³	Assumed equivalent to the density of ice
ε	0.08 m	Minimum layer thickness for even distribution is 0.05 m.; no limit on maximum thickness but freezing rate will decrease as ε increases
θ	0.34	For anaerobically digested sludge, determined by Martel (1989b)
	0.15	For aerobically digested sludge, determined by Martel (1989b)
	0.07	For water treatment sludge, determined by Martel (1989b)
K_{fs}	2.21 W/m°C	Assumed equivalent to the thermal conductivity of ice
K_{ss}	0.35 W/m°C	According to measurements by Vesilind and Martel (1989)
L	93.0 W h/kg	Assumed equivalent to the latent heat of water
α	0.9	Assumed equivalent to absorptance of dry plowed ground which has a color similar to sludge.
T_f	0°C	According to laboratory measurements
τ	0.9	According to manufacturer's literature on the transmittance of fiber-reinforced polyester
$\bar{h}_c$	7.5 W/m²C	According to field measurements
$\bar{T}_{af}$, $\bar{T}_{at}$	Site specific	Nearest meteorological station
$\bar{I}$	Site specific	Kreith and Kreider (1978)
P_f, P_{th}	Site specific	Nearest meteorological station

Table 3. Comparison of predicted to actual depths of frozen sludge.

Year	*Freezing index* $P_f(\bar{T}_f - \bar{T}_{af})$ *(°C·h)*	*Average layer thickness,* ε *(m)*	*Predicted freezing depth,* D_f *(m)*	*Actual frozen depth (m)*
1	7,600	0.097	0.57	0.58
2	12,300	0.076	0.96	1.14
3	10,600	0.074	0.83	0.89

Because of the above assumptions, this model should not be used for sludge freezing operations in uncovered drying beds. The depth of sludge that can be frozen in uncovered drying beds is unpredictable because of the unpredictability of snowstorms.

As shown in Table 3 the freezing depths predicted by this model were in good agreement with the actual depths of frozen sludge obtained in the pilot plant study.

Figure 11. Areas in North America where sludge freezing beds can be used.

The actual freezing depths were slightly higher than the predicted freezing depths, which indicates that the model predictions were conservative when used with the suggested input values. The numerator in the model, $P_f(T_f - T_{af})$, which is the freezing index, was determined from the cumulative degree-hour plots in Figures 4, 8 and 9. The average layer thickness ε was determined by dividing the total depth of frozen sludge by the number of layers applied.

Based on this model the freezing design depth is zero when the freezing index is zero. A rough approximation as to where this occurs in North America can be determined from a freezing index map (Berg and Johnson 1983). As shown in Figure 11 the zero freezing index line runs through the central U.S. and along the Pacific Coast. Below this line a freezing bed would probably not be feasible because freezing cannot be expected to occur on an annual basis. Freezing beds could be used in areas above this line, which includes most of the U.S. and Canada.

The freezing model will control the design wherever freezing occurs on an annual basis and the net gain of energy at the earth's surface is greater than the net energy loss. Generally this occurs in the more temperate regions where there is no permafrost. Based on maps showing the extent of discontinuous permafrost (Lunardini 1981), the approximate northern limit of this region is central Canada (Fig. 11). Above the permafrost line the net gain of energy can be expected to be less than the net energy loss, so not all of the sludge frozen during the freezing period will thaw during the thawing period. Therefore, the design depth in this region will be limited

by thaw. As shown in Figure 11, this region extends to the northernmost areas of the continent, except for ice-covered areas such as Greenland.

Thawing model

A proposed model for predicting the thawing design depth Y is

$$Y = \left[\left(\frac{K_{ss}}{\theta \bar{h}_c}\right)^2 + \frac{2K_{ss}P_{th}}{\theta\beta}\right]^{1/2} - \frac{K_{ss}}{\theta \bar{h}_c} \qquad (2)$$

where β = $\rho_f L / \left(\bar{T}_{at} - T_f + \alpha\tau\bar{I}/\bar{h}_c\right)$
K_{ss} = thermal conductivity of the settled sludge
ρ = fraction of settled sludge per unit depth of thawed sludge
P_{th} = thawing period
$\bar{T}_{at}$ = average ambient air temperature during thaw
α = solar absorptance of the sludge
τ = transmittance of the roof material
$\bar{I}$ = average insolation during the thawing period (Martel 1988c, 1989b)
θ = fraction of settled sludge per unit depth of thawed sludge.

Suggested values for these parameters can also be found in Table 2. The thawing model assumes that

- The bed is covered to keep out precipitation;
- The roof material allows passage of 90% of the incoming solar radiation; and
- There is no supernatant above the frozen sludge, and all meltwater is drained away as quickly as possible.

Table 4 compares the predicted and actual depths of thawed sludge. Values for P_{th} were determined from Figures 4, 8 and 9. $\bar{T}_{at}$ values were determined from climatic data supplied by the Hanover Meteorological Detachment. The settled sludge fractions θ were calculated from Figures 4, 8, and 9 by taking the ratio of final thawed sludge depth to the initial frozen sludge depth. These fractions are similar to those suggested values shown in Table 2, which were derived from laboratory tests. Except for year 1, the thawing design depths predicted by the model were in good agreement with the actual depths.

CONCLUSIONS

The freezing bed was not damaged structurally when sludge was frozen in layers. However, pressure due to the expansion of ice occasionally ruptured the frozen surface of the sludge layer.

During year 1 the freezing bed effectively dewatered 58 cm of anaerobically digested sludge containing 6.7% solids. The average solids content after drainage was 39.3%. During year 3 the freezing bed effectively dewatered 89 cm of aerobically digested sludge containing 1.1% solids. The average solids content after drainage was 24.5%. The meltwater quality from both sludges was roughly equivalent to raw wastewater. The dewatered sludge was easily removed from the bed with a front-end loader.

The freezing and thawing design depths predicted by the models were in good agreement with the actual depths observed during this pilot-scale study.

RECOMMENDATIONS

Meltwater should not be allowed to accumulate in the bed because it can cause an odor problem. Instead, it should be drained away as quickly as it is produced.

The original freezing bed concept should be modified to include trench drains in the bottom of the bed. These drains should be located along the sidewalls of the bed where thawing begins and most of the meltwater is collected.

The bottom of the bed should be covered with a 5- to 8-cm-thick sand layer for effective drainage of meltwater. This sand layer should be replaced each year because it will be removed along with the dewatered sludge.

Table 4. Comparison of predicted depths to actual depths of thawed sludge.

Year	*Thawing period,* P_{th} *(hr)*	*Average air temperature during thaw,* $\bar{T}_h$ *(°C)*	*Avg. insolation,* $\bar{I}$ *(W/m²)*	*Settled sludge ratio,* θ	*Predicted depth of thaw,* Y *(m)*	*Actual thawed depth (m)*
1	1344	7.7	149	0.35	0.74	0.58
2	1800	10.1	172	0.30	1.04	1.14
3	1056	5.4	166	0.15	0.89	0.89

The roof should by opaque rather than transparent if the bed is located in a temperate climate. Otherwise incoming solar radiation may delay freezing in some portions of the bed.

Application of sludge layers should be done automatically for maximum freezing. An automatic sludge applicator is presently under development.

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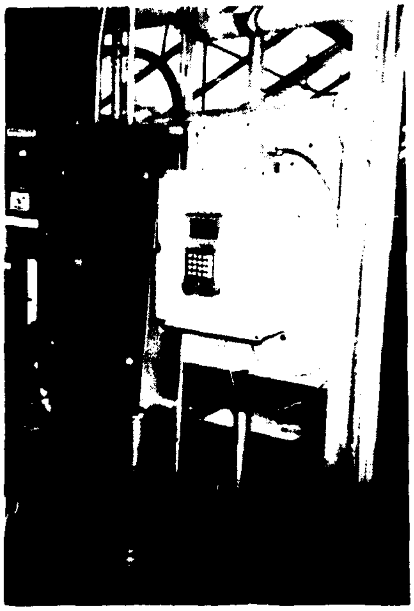
APPENDIX A: DESCRIPTION AND OPERATION OF AN AUTOMATIC SLUDGE APPLICATION DEVICE

The automatic sludge application system (ASAS) was developed to run the sludge freezing bed 24 hours a day, seven days a week. In this way, maximum utilization of cold weather conditions can be realized without having an operator on duty to check the bed and make applications. Should a cold spell occur during a weekend or some other off-duty period, applications could continue without loss of freezing time. Simply described, the ASAS determines whether the last layer applied is frozen, and if so it applies the next layer. The ASAS makes this determination indirectly. The microcomputer takes hourly ambient temperature readings and keeps a running total of the number of freezing degree-hours. When the target number of hours to freeze the previous sludge layer is reached, the ASAS opens a motor-controlled valve long enough to discharge another layer of sludge. Target values of freezing degree-hours and sludge discharge duration are entered into the ASAS by the plant operator.

Figure A1 shows the ASAS. The microcomputer is housed inside a standard waterproof electrical box measuring 36 × 26 × 21 cm. The front panel consists of a keyboard, which the operators uses to enter commands, and a liquid crystal display (LCD). The box also contains a 12-V battery, which serves as the power source. The ASAS unit obtained temperature readings from a thermistor located at the freezing bed. While a motor-controlled valve was used to gravity-feed sludge to the CRREL freezing bed, other facilities could use piston or screw pumps through the ASAS.

As stated before, the freezing degree-hour target value and the discharge duration are entered into the ASAS through the keyboard. To enter the freezing degree-hour value, the operator punches a button labeled °C-hr setpoint. A data entry prompt then appears on the LED display, and the operator simply punches in the proper numbers. To enter the discharge duration, the button labeled discharge duration is pushed and the same procedure is followed. There are also manual override and momentary discharge options that may be used at the operators discretion.

Depending on wind conditions, a 7.5-cm-layer of sludge was found to require 550–1000 freezing degree-hours to freeze solid. It was the general operating pro-



a. Control box.

b. Motorized valve.

Figure A1. Automatic sludge application system.

cedure at CRREL to set the ASAS for the higher figure to be conservative. However, the operator could reset the target value to a lower number during periods of high wind because the bed will require fewer degree-hours to freeze solid. The new target value could be estimated based on the remaining depth of unfrozen sludge in the layer. Also, if the bed was found to be frozen before the value was reached, the operator can apply another layer manually.

Solar radiation striking the dark surface of the sludge and the concrete walls of the bed can thaw some of the previously frozen sludge, even when the ambient air temperature is below freezing. Consequently the ASAS unit could apply the next layer of sludge before the previous layer had frozen. To alleviate this problem, the bed should be shaded to prevent solar heating or checked by the operator before applying the next layer.

The main ASAS control box should be located where it won't be subjected to extreme temperatures. It should also be mounted in a location where other process monitoring takes place, making it easier for an operator to use while overseeing other important plant functions. Extreme care should be taken in choosing the location of the thermistor so that accurate ambient temperatures may be obtained. The thermistor should be sheltered from sunlight and located away from any potential heat sources, such as buildings and other structures.

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In 1986 a pilot-scale sludge freezing bed was constructed at the U.S. Army Cold Regions Research and Engineering Laboratory in Hanover, New Hampshire. This bed was operated over the next three years using both anaerobically and areobically digested sludges. These tests demonstrated that both sludges can be effectively dewatered by this process. The final solid contents were 39.3% and 24.5% for anaerobically digested and aerobically digested sludges, respectively. The quality of the meltwater was similar to raw wastewater. Odors were not a problem if the meltwater was drained away as quickly as it formed. Both sludges were easily removed with a front-end loader. The actual depth of sludge frozen and thawed in the bed during each year of operation was very close to that predicted by design models.

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